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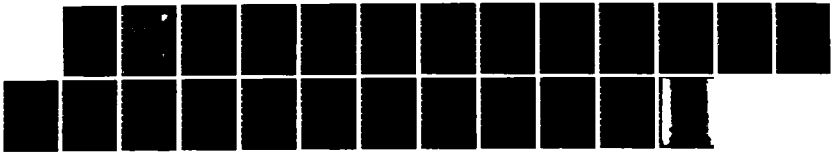

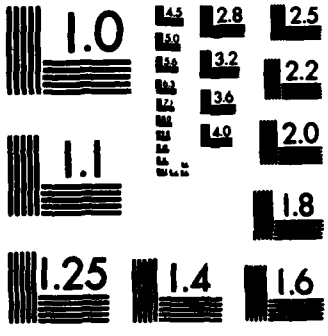

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In-House Report
February 1984

AD-A142 719

NULLING IN ARRAY PATTERNS WITH ORTHOGONAL ANALYTIC CANCELLATION BEAMS

Michael J. O'Brien, Major, USAF

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A method of reducing the coupling between the analytic beams formed to place multiple nulls in the radiation patterns of phased array antennas is developed using cancellation beams that are orthogonal in the sense that each beam has nulls in the directions where the other beams have maximums. A formulation for these beams is presented for arrays in which the element amplitude and phase are adjusted and for arrays in which only the phase is adjusted.

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Contents

1. INTRODUCTION 5
2. BACKGROUND 6
3. DECOUPLED BEAMS 10
4. RESULTS 11
5. CONCLUSION 20

Illustrations

1. Array Geometry 7
2. Quiescent Pattern for a 20 Element Array With Half Wavelength Spacing and Element Excitations for a 30-dB Taylor Distribution With $\bar{n} = 4$ 11
3. Orthogonal Cancellation Beams Using Amplitude and Phase Control to Obtain a Uniform Taper, $c_n = 1$ 13
4. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Amplitude and Phase Control for a Uniform Taper, $c_n = 1$ 13
5. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15° and 26.5° by Amplitude and Phase Control With the $c_n = 1$ 14

Illustrations

6. Orthogonal Cancellation Beams Using Amplitude and Phase Control to Obtain the Taylor Taper, $c_n = a_n$ 15
7. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Amplitude and Phase Control for the Taylor Taper, $c_n = a_n$ 15
8. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15^o and 26.5^o by Amplitude and Phase Control With the $c_n = a_n$ 16
9. Orthogonal Cancellation Beams Using Phase-only Control to Obtain a Uniform Taper, $c_n = 1$ 16
10. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Phase-only Control for a Uniform Taper, $c_n = 1$ 17
11. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15^o and 26.5^o by Phase-only Control With the $c_n = 1$ 17
12. Orthogonal Cancellation Beams Using Phase-only Control to Obtain the Taylor Taper, $c_n = a_n$ 18
13. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Phase-only Control for the Taylor Taper, $c_n = a_n$ 19
14. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15^o and 26.5^o by Phase-only Control With the $c_n = a_n$ 19

Nulling in Array Patterns With Orthogonal Analytic Cancellation Beams

I. INTRODUCTION

The ever increasing capability of jammers is severely limiting the performance of both communication and radar systems. Because communication array antennas typically have a relatively small number of elements, it is practical to employ elaborate adaptive techniques to suppress the jamming interference. It is neither practical nor economically feasible to apply these same techniques to large phased array radar antennas.

It is possible to place nulls adaptively in large phased arrays by adjusting either the amplitudes and phases or only the phases[1] of all the elements in the array or in subsets of the elements.[2] Another approach is to adjust all the elements to form a cancellation beam in the direction of each jammer.[3] As a result, changes in the array pattern are generally constrained to angular regions near the null directions. There are, however, interactions between the cancellation beams in the null directions.

(Received for publication 27 February 1984)

1. Schapov, Yu. M. (1983) Algorithms of random search for adaption of antenna arrays with discrete phase shifters, Izvestiya VUZ. Radioelectronica, Vol. 26, No. 2:80-85.

2. Haupt, R. L., and Shore, R. A. (1984) Experimental Partially Adaptive Nulling in a Low Sidelobe Phased Array, IEEE APS Symposium Proceedings.

3. Baird, C., and Rassweiller, G. (1976) Adaptive sidelobe nulling using digitally controlled phase-shifters, IEEE Trans. Antennas Propag. AP-24:638-649.

This report presents a method of reducing the coupling between the cancellation beams. Beams that are orthogonal in the sense that each beam has a null in the directions where the other beams have a maximum will be decoupled in those directions. Consequently, in an adaptive antenna, the nulls can be placed sequentially with each succeeding nulling operation having minimal effect on previous nulls.

2. BACKGROUND

Analytical beams are a convenient means to view certain null synthesis techniques as well as adaptive nulling techniques. An analytical beam differs from a physical beam in that it is formed and controlled by adjusting the excitation of each array element in a specified manner. A physical beam, on the other hand, is hardware formed (by a Butler Matrix, for example) and is controlled by adjusting the excitation at a single beam port. A review of the general method of forming analytical beams to place nulls in the radiation pattern of a phased array antenna follows.

The antenna shown in Figure 1 is a linear array of N equispaced isotropic elements with the phase reference being the center of the array. The far field pattern, p(u), for the array is given by

$$p(u) = \sum_{n=1}^{N} w_n \exp(jd_n u) \quad ,$$

where

$u = kd \sin\theta$;

d = element spacing;

$k = 2\pi/\lambda$, λ being the wavelength;

$d_n = n - (N + 1)/2$;

θ = angle measured from broadside to the array;

and

w_n = element excitation.

We wish to perturb the element excitations to form nulls in the array pattern in the directions; $u = u_m$, $m = 1, 2, \ldots M$.

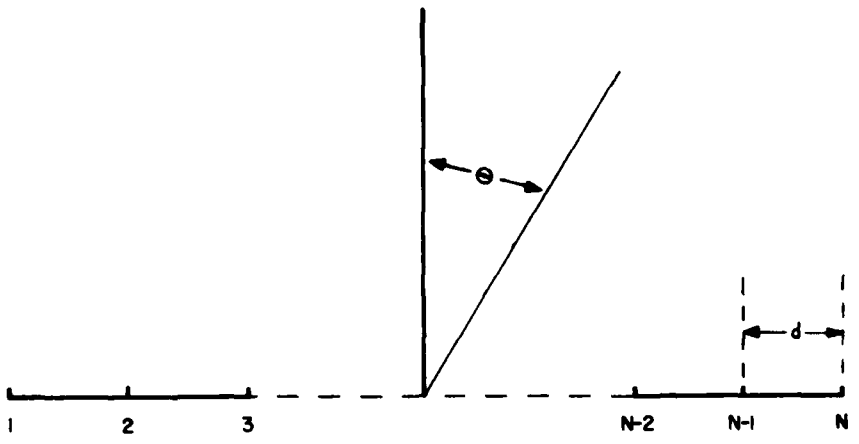

Figure 1. Array Geometry

In general, the array has an amplitude taper, a_n, and is steered in the direction $u = u_s$. Therefore, the unperturbed or quiescent element coefficients are

$$w_{qn} = a_n \exp(-jd_n u_s) \quad .$$

The amplitude taper is assumed to have even symmetry about the array center while the phase is known to have odd symmetry since

$$d_n = -d_{N+1-n} \quad .$$

Let the perturbed weights be represented as

$$w_n = w_{qn} + \Delta w_n \exp(-jd_n u_s)$$

with

$$\Delta w_n = \Delta_n + j\delta_n \quad .$$

Hence, the perturbed array pattern p(u),

$$p(u) = \sum_{n=1}^{N} \{w_{qn} \exp(jd_n u) + \Delta w_n \exp[jd_n(u - u_s)]\} \quad .$$

consists of two separate patterns. The first is just the quiescent pattern, and with the proper Δw_n the second is the cancellation pattern. To determine the Δw_n, we require the perturbed pattern to have nulls in the desired u_m directions. Imposing this requirement results in a set of M equations with N variables.

Shore and Steyskal[4] derived solutions for the general problem where the number of elements, N, exceeds the number of desired nulls, M. Their report considers null steering by perturbing both the amplitude and the phase or by perturbing just the phase. The solution when both the amplitude and the phase are controlled can be written in the form;

$$\Delta_n = c_n \sum_{m=1}^{M} b_m \cos [d_n(u_m - u_s)]$$

$$\delta_n = c_n \sum_{m=1}^{M} b_m \sin [d_n(u_m - u_s)] \quad ,$$

where the coefficients c_n represent a taper function that specifies the form of the cancellation pattern, and has the same symmetry as the a_n, while the b_m represents the amplitude of the cancellation beam steered to the $u = u_m$ direction.

When only the phase is controlled, the perturbed coefficients become

$$w_n = w_{qn} \exp (j\Delta\phi_n) \quad .$$

Assuming small phase perturbations, which is a valid assumption for a low sidelobe quiescent pattern,

$$\exp (j\Delta\phi_n) \approx 1 + j\Delta\phi_n \quad .$$

Therefore, the perturbed pattern becomes

$$p(u) = p_q(u) + j \sum_{n=1}^{N} a_n \Delta\phi_n \exp [jd_n(u - u_s)] \quad .$$

---

4. Shore, R.A., and Steyskal, H. (1982) Nulling in Linear Array Patterns With Minimization of Weight Perturbation, RADC-TR-82-32, AD A118695.

The $\Delta\phi_n$ that cause p(u) to have nulls in the desired directions are of the form

$$\Delta\phi_n = (c_n/a_n) \sum_{m=1}^{M} b_m \sin [d_n(u_m - u_s)] \quad .$$

The coefficients c_n and b_m represent the parameters as described above.

For either the amplitude-phase or the phase-only solution, the cancellation pattern may be considered as a superposition of M beams, $P_m(u)$. However, for each cancellation beam formed by phase-only control there is a concomitant beam in the $u = -u_m + 2u_s$ direction.

Consequently, the perturbed pattern is

$$p(u) = p_q(u) + \sum_{m=1}^{M} b_m P_m(u) \quad ,$$

where the cancellation beams $P_m(u)$ for both amplitude and phase control are

$$P_m(u) = \sum_{n=1}^{N} c_n \exp [jd_n(u - u_m)] \quad ;$$

and those for phase-only control are

$$P_m(u) = \sum_{n=1}^{N} c_n \sin [d_n(u_m - u_s)] \exp [jd_n(u - u_s)] \quad .$$

The nulling requirement is now reduced to solving for the beam coefficients, b_m, such that

$$p(u_\ell) = p_q(u_\ell) + \sum_{m=1}^{M} b_m P_m(u_\ell) = 0, \qquad \ell = 1, 2, \ldots M \quad . \tag{1}$$

3. DECOUPLED BEAMS

In Section 2 we saw that the cancellation pattern consisted of a sum of cancellation beams, $P_m(u)$. In order to place a null in a given direction the sum of these beams must cancel the quiescent pattern in the given direction. In other words, all beams contribute in producing each null. This beam interaction may be undesirable in an adaptive antenna.

Suppose we wish to reduce the interaction between the beams. One approach is to form low sidelobe cancellation beams so that the cancellation beam in the desired direction is the only one to contribute significantly. Another approach is to let a new cancellation beam in the u_k direction for $k = 1, 2, \ldots M$ be composed of a weighted sum of the $P_\ell(u)$. This composite cancellation beam is thus

$$B_k(u) = \sum_{\ell=1}^{M} a_{\ell k} P_\ell(u) \quad .$$

To reduce coupling between these cancellation beams we now require that

$$B_k(u_\ell) = 0, \quad \text{for} \quad \ell \neq k$$

to obtain the following sets of equations:

$$\underline{D}\,\underline{S}\,\underline{A}_k = 0, k = 1, 2, \ldots M \quad . \tag{2}$$

Here $\underline{S}$ is the Hermitian matrix with elements

$$S_{k\ell} = P_\ell(u_k) \quad ;$$

$\underline{A}_k$ is the k^{th} column vector of the coefficient matrix $\underline{A}$ with diagonal elements $a_{ii} = 1$. $\underline{D}$ is a (diagonal) matrix with elements d_{ji} ($d_{ij} = 0$, $i \neq j$) and diagonal elements $d_{ii} = 1 - \delta_{ik}$, where δ_{ik} is the Kroneker delta function

$$\delta_{ik} = \begin{cases} 1 & i = k \\ 0 & i \neq k \end{cases} ,$$

and k is the column of $\underline{A}$. With this added condition, Eq. (2) can now be solved. The perturbed far-field pattern is the sum of the quiescent pattern and the composite cancellation beams. Accordingly,

$$p(u) = p_q(u) + \sum_{k=1}^{M} b_k B_k(u) \quad .$$

Since $B_k(u_\ell) = 0$ for $\ell \neq k$, the requirement to place a null in the u_k direction is satisfied when

$$b_k = -p_q(u_k)/B_k(u_k) \quad .$$

4. RESULTS

The results presented in this section are typical of those obtained using the formulation described in the previous section. All computations were performed for an array consisting of twenty isotropic elements with a spacing of half a wavelength. The quiescent weights are for a 30-dB Taylor distribution with $\bar{n} = 4$. The corresponding quiescent pattern is shown in Figure 2. The desired nulling directions are 15° and 26.5°.

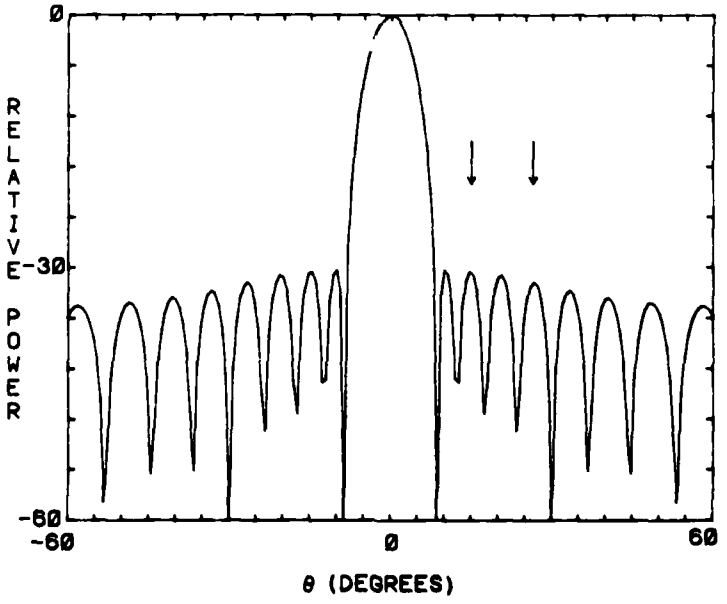

Figure 2. Quiescent Pattern for a 20 Element Array With Half Wavelength Spacing and Element Excitations for a 30-dB Taylor Distribution With $\bar{n} = 4$

The cases are divided in two sets according to the type of element control applied. In the first set, both the amplitude and the phase are perturbed while in the second set only the phase is perturbed. In each of these sets two different taper functions are applied. The first taper is the uniform taper, $c_n = 1$, and the second taper is the same as that for the quiescent weights, $c_n = a_n$. The uniform taper results in a composite cancellation beam for which the $P_\ell(u)$ are sinc patterns. Hence,

$$B_1(u) = P_1(u) + a_{21} P_2(u)$$

and

$$B_2(u) = a_{12} P_1(u) + P_2(u) \quad ,$$

where

$$P_1(u) = \sin [10(u - \pi \sin 15^\circ)] / \sin [(u - \pi \sin 15^\circ)/2]$$

and

$$P_2(u) = \sin [10(u - \pi \sin 26.5^\circ)] / \sin [(u - \pi \sin 26.5^\circ)/2]$$

Since the elements of $\underset{\sim}{S}$ are $S_{k\ell} = P_\ell(u_k)$, and the $P_\ell(u)$ are given above, $\underset{\sim}{S}$ becomes

$$\underset{\sim}{S} = \begin{bmatrix} 20 & -1.33 \\ -1.33 & 20 \end{bmatrix} .$$

The resulting coefficient matrix $\underset{\sim}{A}$ is

$$\underset{\sim}{A} = \begin{bmatrix} 1 & 0.0666 \\ 0.0666 & 1 \end{bmatrix} .$$

Figure 3 shows both composite cancellation beams. Note that each beam has a null in the direction in which the other beam is maximum. The sum of these composite beams forms the cancellation pattern in Figure 4 which also includes the quiescent pattern for comparison. Finally, the perturbed pattern is shown along with the quiescent pattern in Figure 5. The important feature of Figure 5

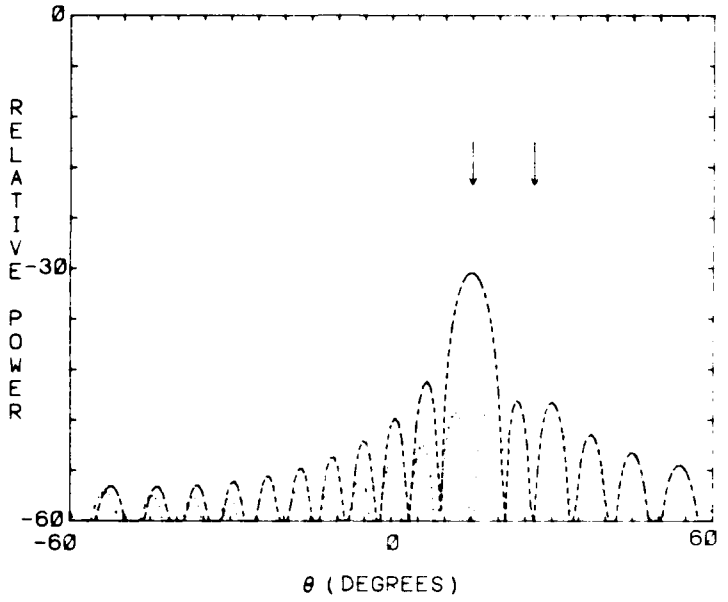

Figure 3. Orthogonal Cancellation Beams Using Amplitude and Phase Control to Obtain a Uniform Taper, $c_n = 1$

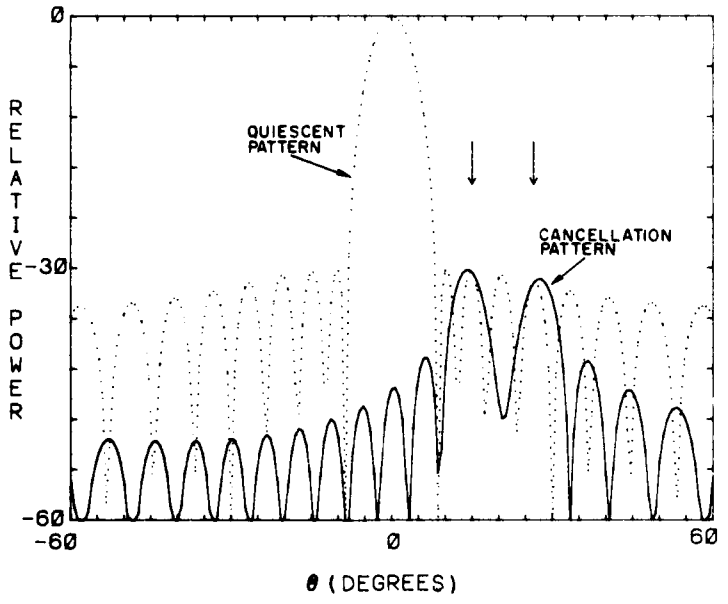

Figure 4. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Amplitude and Phase Control for a Uniform Taper, $c_n = 1$

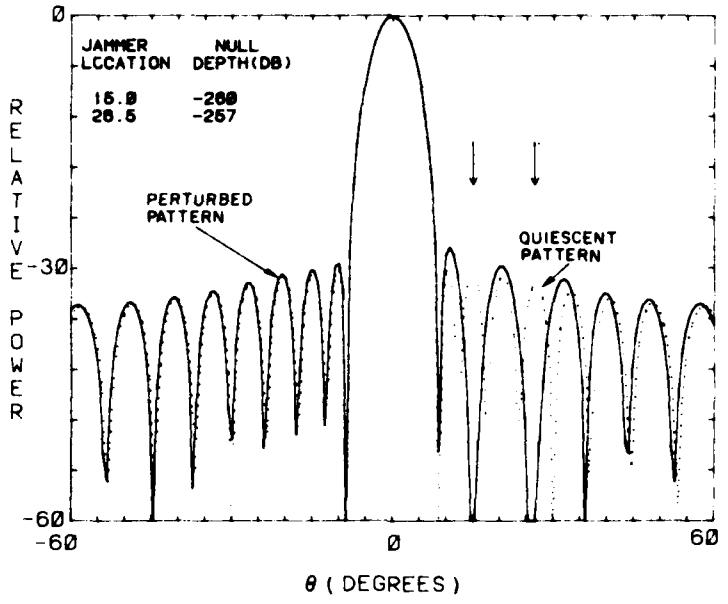

Figure 5. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15° and 26.5° by Amplitude and Phase Control With the $c_n = 1$

is the small differences between the two patterns everywhere except near the two nulls.

Both amplitude and phase control are applied for Example 2, but here $c_n = a_n$. For this taper the $P_f(u)$ have the same form as the quiescent pattern. As with the uniform taper above, each composite cancellation beam in Figure 6 has a null in the direction of the other's maximum. The cancellation pattern of Figure 7 produces the perturbed pattern in Figure 8. Although the differences between the quiescent pattern and the perturbed pattern are still small, they are greater than those in Figure 5. Because of the taper, the cancellation beams in Figure 6 are broader than those for the uniform taper in Figure 3. Consequently, the broader beams disturb the pattern more in the null region.

The remaining set of examples demonstrates the cancellation beams formed by phase-only control. Again the first example uses a uniform taper, and the second uses the same taper as for the quiescent weights.

Figure 9 shows the composite cancellation beams for the two null directions along with the concomitant beams in the $\theta = -15^{\circ}$ and $\theta = -26.5^{\circ}$ directions. These beams combine to form the cancellation pattern in Figure 10. The perturbed pattern in Figure 11 differs from the quiescent pattern not only in the regions near the nulls but also in the regions symmetric to the main-beam. In

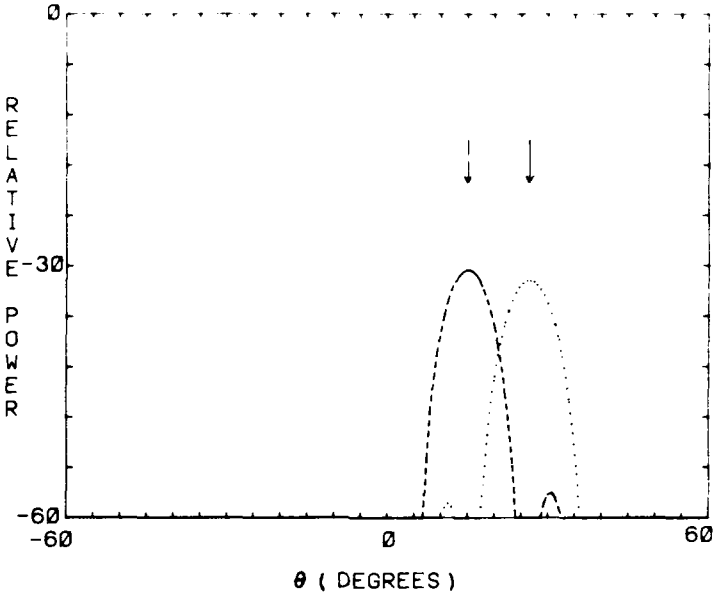

Figure 6. Orthogonal Cancellation Beams Using Amplitude and Phase Control to Obtain the Taylor Taper, $c_n = a_n$

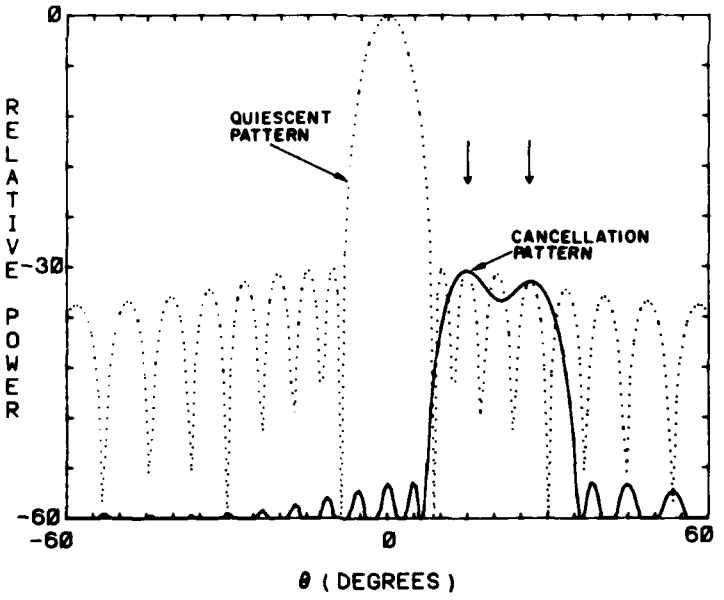

Figure 7. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Amplitude and Phase Control for the Taylor Taper, $c_n = a_n$

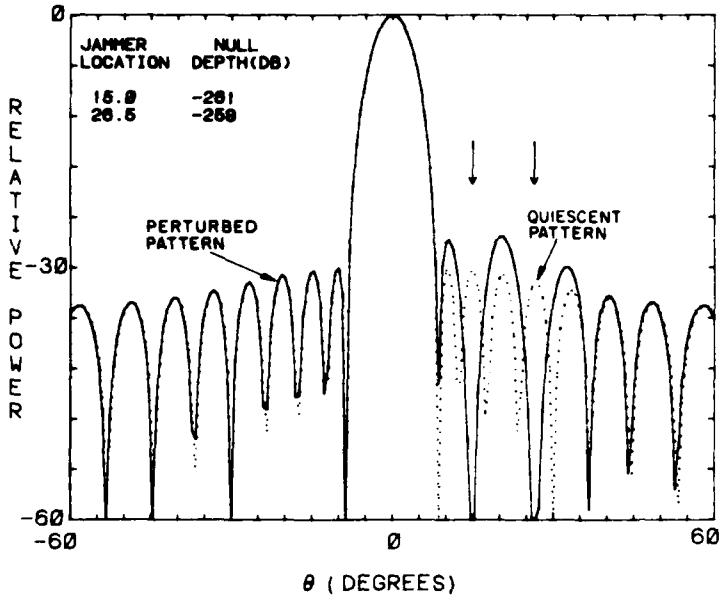

Figure 8. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15° and 26.5° by Amplitude and Phase Control With the $c_n = a_n$

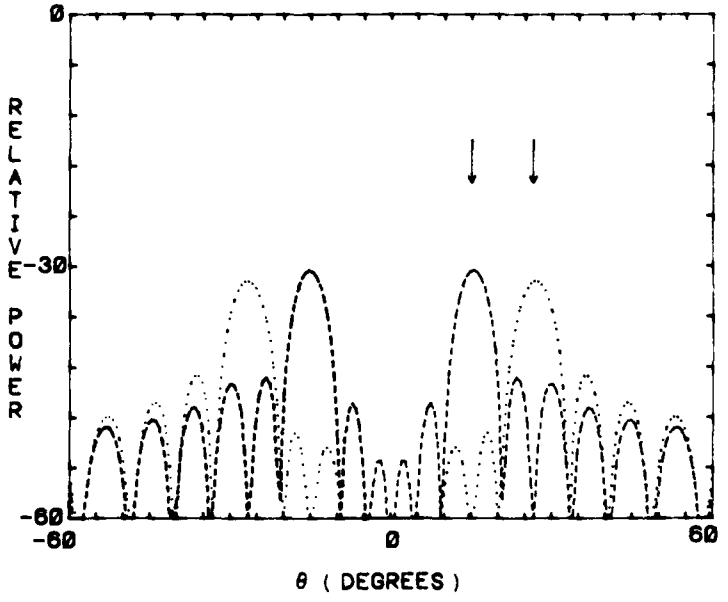

Figure 9. Orthogonal Cancellation Beams Using Phase-only Control to Obtain a Uniform Taper, $c_n = 1$

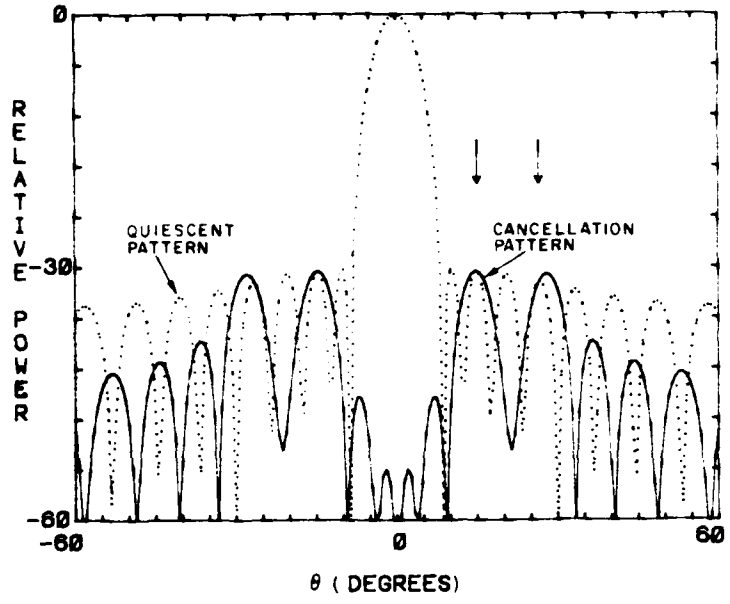

Figure 10. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Phase-only Control for a Uniform Taper, $c_n = 1$

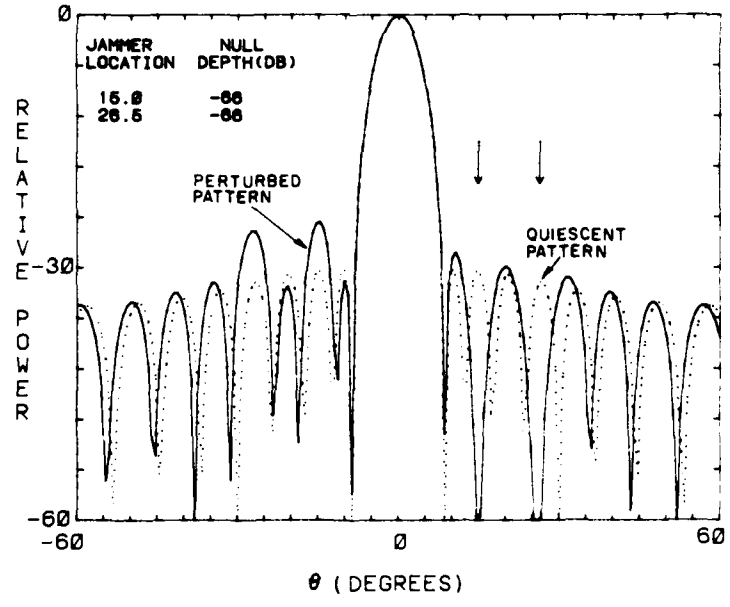

Figure 11. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15° and 26.5° by Phase-only Control With the $c_n = 1$

fact, since the cancellation pattern adds in phase with the quiescent pattern in these regions, the symmetric sidelobes have increased approximately 6 dB.

Figure 12 shows the cancellation beams for phase-only control with the same taper function as that for the quiescent weights. As with the previous examples the beams are decoupled in the null directions. The cancellation pattern in Figure 13 combines with the quiescent pattern to form the perturbed pattern in Figure 14. The perturbed pattern has the combined effects of the taper as shown in Figure 8 and the phase-only control as shown in Figure 11.

Besides the increase in sidelobe levels at the symmetric locations in the pattern, the use of phase-only nulling appears to limit the null depth that can be achieved. For the ideal, error-free antenna considered, the nulls are significantly lower when both amplitude and phase are controlled than when only the phase is controlled. However, this limit is not due to phase-only control. Instead, it is due to the finite accuracy of the linear approximation for small phase perturbations. In practice, the nulls will be achieved adaptively rather than deterministically. The adaptive technique can at least partially compensate for this finite accuracy.

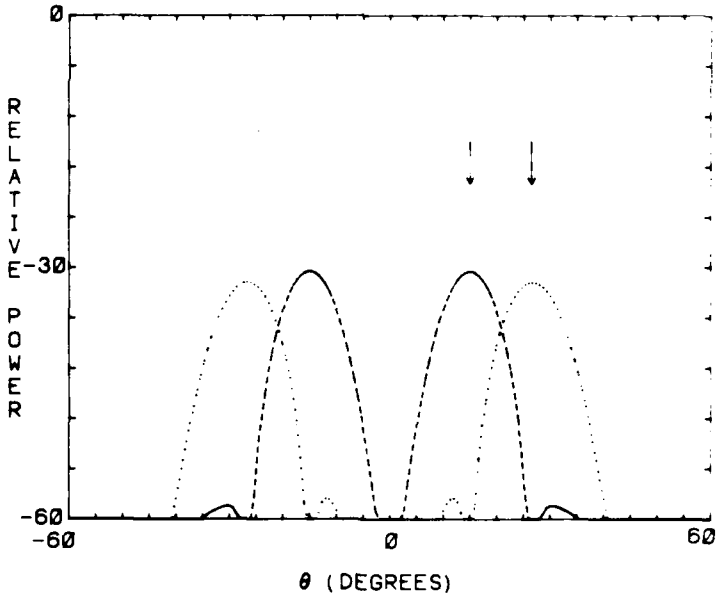

Figure 12. Orthogonal Cancellation Beams Using Phase-only Control to Obtain the Taylor Taper, $c_n = a_n$

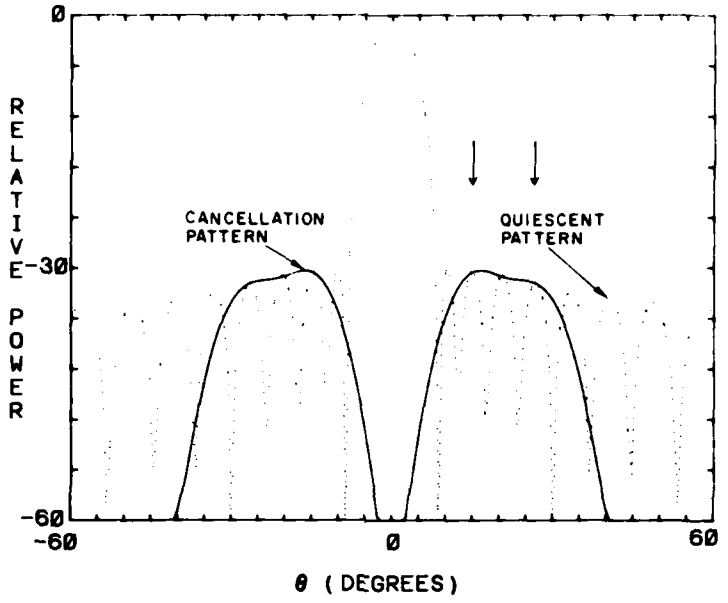

Figure 13. Quiescent Pattern and Cancellation Pattern Resulting From Cancellation Beams Formed by Phase-only Control for the Taylor Taper, $c_n = a_n$

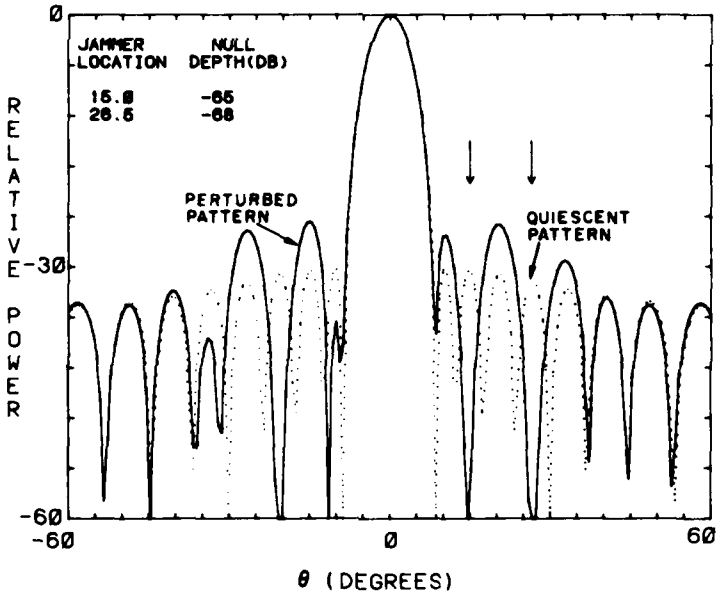

Figure 14. Quiescent Pattern and Perturbed Pattern With the Desired Nulls Imposed at 15^{o} and 26.5^{o} by Phase-only Control With the $c_n = a_n$

5. CONCLUSION

The method presented in this report forms the basis for the development of additional adaptive techniques for large radar array antennas. The decoupled analytic cancellation beams allow greater flexibility in the adaptive process, such as selectively nulling in certain directions. The use of analytic beams, in general, constrains the pattern perturbations to angular regions near the desired null locations and near the symmetric regions for phase-only control. The use of the decoupled beams further constrains the perturbations to a single null region and (with phase-only control) the symmetric region for a given beam.

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